Fuel 129 (2014) 330–339

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Experimentally determined storage and handling properties of fuel pellets made from torrefied whole-tree pine chips, logging residues and beech stem wood

T. Järvinen [a], D. Agar [b,*]

[a] Technical Research Centre of Finland (VTT), P.O. Box 1603, 40101 Jyväskylä, Finland
[b] Åbo Akademi University, Process Chemistry Centre, Piispankatu 8, FI-20500 Turku, Finland

HIGHLIGHTS

- Measured properties of torrefied pellets made from pine, logging residues and beech.
- Pellets produced at two semi-industrial pilot-scale torrefaction plants.
- Properties include: calorific value, bulk density, energy density, durability, EMC.
- Results useful for evaluation of co-firing at pulverised coal plants.

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form 24 March 2014
Accepted 25 March 2014
Available online 13 April 2014

Keywords:
Torrefaction
Torrefied pellets
Co-firing
Pellet properties
Bio-coal

ABSTRACT

Torrefaction is currently of interest for the production of a new generation of fuel pellets suitable for increasing co-firing rates at pulverised-coal power plants. However, few results have been reported on properties of pellets which can currently be produced from torrefied materials. This data is required in order to evaluate the suitability of this fuel for its primary application.

The objective of this study was to obtain measured results on storage and handling properties of pellets made of torrefied pine, logging residues (with and without wheat flour binder) and beech. Experimental methods, most of which adhere to standard procedures, are described. The measured properties include calorific value, bulk density, durability, hardness and equilibrium moisture content (EMC). Additionally, EMC isotherms of torrefied beech wood are presented. The results are analysed and their influence on the feasibility of large-scale pellet production is discussed. The measured and derived values presented will be of use in determining feasibility of torrefied pellet production in offsetting the use of fossil coal.

From the results the following statements can be made regarding produced pellet samples:

- Feedstock choice has a strongly influence on properties of torrefied pellets.
- Durability of torrefied pellets is problematic compared to wood pellets.
- Outdoor heap storage of torrefied pellets is not recommended.
- Logging residues do not seem to be an optimal feedstock choice for torrefied pellets.
- Wheat flour does not appear suitable as binder for torrefied pellets production due to water absorption.
- Pelletising using high die temperature (above 170 °C) should be investigated.

© 2014 Elsevier Ltd. All rights reserved.

---

* Corresponding author. Tel.: +358 408054127.
E-mail address: david.a.agar@jyu.fi (D. Agar).

http://dx.doi.org/10.1016/j.fuel.2014.03.057
0016-2361/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

T	temperature (°C)
$q_{V,gr,d}$	gross calorific value at constant volume (MJ kg^{-1})
$q_{p,net,m}$	net calorific value at constant pressure (MJ kg^{-1})
Δq	relative calorific value increase (%)
m_M	mass of moisture in fuel (kg m^{-3})
m_d	mass of dry fuel (kg m^{-3})
M	moisture content (%)
M_{ar}	moisture content as received (%)
M_w	moisture content of fuel on wet basis, $100m_M\,[m_d + m_M]^{-1}$ (%)
M_{15}	moisture content of fuel after 15-min water immersion (%)
$M_{2.5}$	moisture content of fuel after simulated rainfall of 2.5 mm h^{-1} (%)
$w(H)_d$	hydrogen content in dry fuel (%)
$w(O)_d$	oxygen content in dry fuel (%)
$w(N)_d$	nitrogen content in dry fuel (%)
EMC	equilibrium moisture content of fuel (%)
RH	relative humidity (%)
ρ	bulk density (kg m^{-3})
ρ_d	bulk density on dry basis (kg m^{-3})
ρ_M	bulk density at moisture content (kg m^{-3})
σ	energy density (GJ m^{-3})
σ_d	energy density on dry basis (GJ m^{-3})
c_E	energy unit conversion constant, 0.001 (GJ MJ^{-1})
d	mechanical durability (%)
h	pellet hardness in kilogram weight equivalent (kg)

1. Introduction

The desire to generate energy more sustainably has fuelled renewed interest in biomass fuels. The physical properties of biomass as a fuel differ from coal in the following ways.

- Low calorific value.
- Low bulk density.
- High moisture content.
- Low friability.
- More heterogeneous nature.

Grate and fluidised-bed boiler technologies are designed to utilise fuels with the properties listed above and indeed firing biomass in these boilers is already widely practiced especially in Nordic countries. Pulverised fuel boilers however are exclusively designed for coal with good economics in mind. Fossil coal is still widely used throughout Europe and the world in large-scale power plants [1]. The most cost-effective method of co-firing biomass in such plants is to mix it with coal which is known as *direct co-firing*. Although this sounds straightforward co-combustion in practice is limited by the extra costs of biomass pre-treatment (extra handling and milling requirements), additional operational costs from using non-coal fuels and any required retrofitting of the boiler [2]. Other important factors at the fuel yard are how biomass affects the conveying of the mix to the boiler. Due to a difference in flow properties mixtures can bridge and form plugs in conveying lines and channels. These factors among others usually limit feasible rates of co-firing to 5–10% of thermal fuel input at plants designed to burn pulverised coal [2].

Wood pellets are one type of biomass fuel that has been co-fired with coal. The production and use of wood pellets has grown rapidly in recent years. Pellets are made from untreated sawdust and cutter shavings from mostly pine and spruce both by-products of wood processing industry. Pellet production conforms to standard methods in order to ensure minimum requirements are met with regard to fuel properties (i.e. calorific value, moisture content, mechanical durability, fines content &c.). For instance, a survey of Finnish wood pellet properties from five different producers has found that net calorific values range from 18.8 to 19.0 MJ kg^{-1} with bulk densities of 560–690 kg m^{-3}. Pellets absorb moisture and disintegrate readily and therefore are usually packed in large sacks and are protected from the elements. Their moisture content ranges from 7% to 12% and energy density 9.3–12.3 GJ m^{-3} [3]. A similar range of 9.7–11.3 GJ m^{-3} is found for Swedish-produced wood pellets [4]. Wood pellet durability value describes the fraction of pellets which retain their form during transport and handling processes without going to pieces. This may include the formation of fine dust particles. The achieved durability of pellets is routinely above 97.5% but there exists a minimum nominal classification 95.5% according to standards (EN 15210). Hardness is another indicator of pellet quality. Although not existing as a standard, pellet hardness is a commonly used measurement to describe a pellet's resistance to different types of forces. The *Amandus Kahl* hardness tester applies a radial force to a single pellet and hardness is quantified in units of kilogram equivalent. Typical values for wood pellets lie in the range 17–21 kg [3]. *Meyer* hardness is evaluated using a static axial force on the pellet – not a radial force as in *Kahl* testing.

Despite their many benefits co-firing with wood pellets is still subject to limitations at coal plants. With the aim of further increasing co-firing rates the thermal pre-treatment of biomass has become a topic of interest in the energy sector. A process known as *torrefaction* may lead to a new generation of fuel pellets which could enable substantial increases in co-firing rates. Although torrefied fuels may find application at small and medium-scale combustion and heating plants, their main venue is expected to be large pulverised fuel boilers because of their enhanced properties.

Torrefaction is a roasting process, or incomplete pyrolysis, carried out under inert atmosphere; although small amounts of oxygen may prove to be more feasible and even beneficial for industrial applications [5,6]. The aim of torrefaction is to decompose the hemicellulose component of the feedstock using modest temperature (220–300 °C) while avoiding excess gasification of cellulose and lignin components. Like different coffee bean roasts, the extent of torrefaction can be controlled through torrefaction temperature T and residence time of the feedstock in the reactor; the former being the more important parameter [7]. Thermal integration of pyrolysis gases formed during torrefaction is an objective in nearly all torrefaction process concepts to date in order to maximise thermal efficiency [8,9]. Some studies have investigated gas composition [10,11] but research into technical realisation which depends on employed reactor design is not well documented.

Torrefaction reactor and process technologies are currently being evaluated worldwide but despite the technical details three key properties of the resulting torrefied biomass for co-firing have been identified [12]: calorific value, equilibrium moisture content (EMC) and friability of the biomass.

Studies have shown that different biomass feedstock thermally decompose in a similar manner with the energy content yield of the solid product exceeding that of the mass yield [7,10,11,13–17]. These studies show that torrefaction can improve the calorific value of the feedstock by 7–21% resulting in gross calorific values in the range 20.3–23.6 MJ kg^{-1} for woody biomass [12]. Additionally most of the feedstock is conserved with a corresponding range of solid mass yields of 61–82%.

The dry mass fraction of hemicellulose in wood can range from 20% to 30%. Softwood hemicellulose composition however differs from that of hardwood and is mostly (approximately 20%) composed of galactoglucomannans rather than glucuronoxylan [18]. Differences between the rates of thermal decomposition of these two polysugars has been suggested to lead to greater increase in calorific value seen in hardwoods under otherwise equivalent torrefaction conditions [10,11].

Torrefied wood has a lower EMC which has been correlated with a decrease in the concentration of carboxylic acid groups [19]. In solid fuel low moisture content equates to greater net calorific value. Reported results for EMC of different wood species after torrefaction are for the most part in good agreement; though it is not always clear whether reported values are on a wet or dry basis. For example, spruce wood torrefied at 260 °C had an EMC of some 9% at temperature 23 °C and 75% relative humidity (RH) compared to 12% EMC when untreated. Similarly for pine wood the EMC was found to decrease from 15.6% to 8.7% at 30 °C and 84% RH after torrefaction at 275 °C [14]. The same values of EMC are reported by a different author using the same feedstock but for torrefaction at 300 °C [20]. At lower relative humidity (11% RH) they report EMC of the same material torrefied and untreated as 3.5% and 2.2% respectively. From these EMC values at different RH it is noted that differences in EMC for torrefied and raw feedstock are greater at higher RH [14].

Pine and logging residue chips were torrefied using a temperature ranging from 225 to 300 °C. The reported moisture content (wet basis) ranged from 2.6% to 3.3% for pine and 2.4 to 3.1% for residues. The corresponding moisture of the untreated samples was 6.7% and 7.9% [13]. These are not reported as EMC because temperature and RH are not stated, making any comparison questionable. However, assuming all samples were kept under the same conditions, this gives a good indication of how torrefaction affects water uptake ability. Specific particle density of biomass may influence its moisture content so that measured results of EMC of loose feedstock should be considered separately from densified products [21].

After torrefaction the energy required for size reduction of biomass is reduced. A 68–89% reduction in the energy needed for grinding after torrefaction at 275 and 280 °C has been reported [12,13,22]. The improved friability of torrefied biomass fuel makes pulverisation in coal mills easier but also has disadvantages for fuel production. The greater the extent of torrefaction, the greater fraction of fine particles produced through grinding [15,22]. This is expected to increase dust formation during handling. That dust poses a serious fire and explosion risk is well known and appears to be enhanced by torrefaction [23]. Such risks are intensified in enclosed spaces where upgraded fuels are produced and stored.

Studies cited above are all from laboratory-scale investigations in which pelletisation of torrefied materials is not considered. It has been shown that torrefaction of woody feedstock reduces its bulk density [13,24,25]. Despite the improvement in calorific value, the fact that the volume of chipped material does not change appreciable after torrefaction [26] means that energy density (energy per cubic metre) of torrefied material is about the same or less than that original feedstock. This has been shown by Peng et al. for North American species of spruce, pine and fir whose (gross) energy density as sawdust after torrefaction at 280 °C for 52 min has a range of 3.4–4.2 GJ m^{-3}; the range for the same raw (both dried and wet) samples is 3.7–4.3 GJ m^{-3} [24,25]. After grinding and sieving to 1.5 mm particle size however Phanphanich et al. measured bulk densities which give a higher (gross) energy density range of 7.3–8.2 GJ m^{-3} for pine and logging residues torrefied at 275 °C for 30 min – an improvement over the raw value range of 6.6–7.0 GJ m^{-3} [13].

Pelletisation of torrefied biomass is therefore desirable for transport economy, for improving handling and feeding characteristics and achieving a more energy-dense product. The *ability to pelletise* torrefied biomass is then also seen as a key property of a fuel designed for co-firing.

Semi-industrial pellet mills however require large amounts of torrefied feedstock to make sample batches of pellets. Such quantities are not available in small-scale laboratory studies. Many companies and research organisations have been pelletising torrefied material over the last decade but analysis of their products is done internally. This has meant that pellets made of torrefied materials have not been readily available to academic researchers for analysis but this situation is changing through research co-operation and international projects. Herein the term *torrefied pellets* means *pellets made of torrefied biomass*. This definition is necessary to distinguish between these and conventional wood pellets which have been torrefied after production which are also a subject of research.

Although it is commonly known that pelletisation becomes more challenging with extreme torrefaction conditions, quantitative investigations have only recently emerged. At present the only detailed study to produce torrefied pellets on a semi-industrial scale was done by Larsson et al. They investigated pelletisation of Norway spruce after torrefaction at 270 and 300 °C using a semi-industrial pellet press (Bühler DPCB). They measured the energy required and found it to be 100% higher than for pelletising untreated softwood [4]. The torrefied spruce pellets produced (8 mm diameter) had slightly greater bulk densities (630–710 kg m^{-3}) than conventional wood pellets but high amount of fines (10–30%) and significantly lower durability (80–90%). They report energy densities ranging from 12.3 to 14.7 GJ/m^{-3} [4].

Using lab-scale reactors, researchers have been able to produce individual pellets from torrefied material using single pellet presses. Determination of pellet quality in these cases is limited to hardness testing because a mechanical durability test requires at least 500 g of pellets. The *Meyer* hardness of single pellets produced from torrefied sawdust by Li et al. was found to be much less than that made of untreated sawdust. For sawdust torrefied at 240–300 °C the hardness value proved to be roughly half that of the untreated sawdust pellet. In their study, the *Meyer* hardness was measured after pelletising with a die temperature maintained at 170 °C [27]. The study by Peng et al. has shown that hardness (Meyer) of individually produced torrefied pellets depends on die temperature of the press (and mass yield of torrefaction). They found that "strong" pellets require die temperatures of at least 230 °C [24,25]. Though a strong correlation exists between pellet hardness and durability [28,29], hardness alone does not suffice as an indicator of pelletisation success according to existing standards for pellet quality.

Reporting on the making of single pellets, Li et al. measured the energy needed for both compaction and extrusion of sawdust torrefied at 260–300 °C. Their data describes a 29–71% increase for compaction and 280–530% increase for extrusion although specific energy needed for the latter is much lower [27]. Based on the work of Stelte et al. who studied the pelletising process using torrefied spruce and wheat straw, the reason for these energy increases is greater frictional forces present in the die of the pelletiser. They found that friction in the press channel of a single-pellet press increased by a factor of 10–30 between torrefaction temperatures 250 and 300 °C. This in turn led to higher measured pressures [30,31].

Greater frictional forces between particles also seem a likely cause of what Larsson reports as difficulties with regard to the flow of torrefied material (especially for spruce torrefied at 300 °C) during pellet making due to the bridging of material in the conveyor system. This effect was worsened by the addition of water to the mix – in contrast to conventional pellet making. Based on their work Larsson suggests that pelletising with higher die temperature is one alternative to reduce energy consumption.

It has long been held that lignin in woody biomass has been responsible for the relative ease of pelletisation and good mechanical durability of conventional wood pellets [32]. The softening of lignin during mild heating from compaction and its re-hardening after pressing is said to provide the glue between particles and a shiny pellet surface. In chemical terms this mechanism has been described as hydrogen bonding at the lignin and cellulose surface areas [32]. Mainly hemicellulose degradation during torrefaction has meant that most of the feedstock lignin is conserved. The lignin content of the solid product is then expected to increase significantly through torrefaction for woody biomass. Indeed for pine chips and logging residues torrefied at up to 300 °C lignin content has been reported to increase to 80–85% from the initial 26% in the untreated feedstock [13]. Why then in the few findings described above does pellet durability and hardness appear inferior when using torrefied materials? One explanation put forward by Li et al. is that only low molecular weight lignin polymers play a role in lignin softening for untreated wood and that these polymers are also the first to degrade during pyrolysis [27].

An early report on pellets made of torrefied wood made no mention of durability problems with produced pellets. On the contrary, the ECN report which in many ways has “set the bar” for pellet properties expectations finds that the durability of torrefied pellets are better than conventional pellets [26]. This implies a durability rating higher than 98% which is routinely achieved with commercially produced wood pellets. Pellets produced from torrefied sawdust as reported by Bergman also possess between 150% and 200% greater hardness compared to conventional pellets. Although the hardness measurement method is not stated, in terms of *Kahl* hardness values this would correspond to 28–47 kg. For pellets made from torrefied larch wood the improved hardness is 250% or almost 52 kg in *Kahl* units. Several ECN publications are available regarding their work with torrefaction that support these findings [26,8,33].

EMC values for torrefied pellets are not reported by ECN or Larsson. However both authors report similar moisture levels in their produced pellets after cooling – values ranging from 1% to 5%. Under optimal production conditions, Bergman also reports a water uptake of only 7–20% (basis not specified) after a 15-h water immersion test [26]. Returning to individually produced pellets, a minimum moisture content of 12–12.5% is reported for pelletised sawdust after torrefaction at 290–300 °C and stored for 48 h at 30 °C and 90% RH [27]. For pellets of untreated sawdust the EMC was 20.7%.

What is clear from these few studies is that much more research is needed on the properties of pellets produced from torrefied biomass at semi-industrial scales. Information on storage and handling properties of a fuel is important in order to realistically determine its feasibility; especially if it is meant to replace an existing fuel which at present seems to be the most economical. Without detailed characterisation of pellet properties the co-firing potential of these pellets cannot be evaluated.

The objective of the study described herein was to investigate the suitability of Finnish indigenous biomass for torrefied pellet production on a semi-industrial scale and to determine the basic physical properties of these pellets. These properties include the calorific value, bulk density, energy density, equilibrium moisture content, mechanical properties of the pellets (durability and hardness) and their resistance to water.

2. Materials and methods

2.1. Torrefaction of feedstock

The torrefied pellet samples characterised herein were produced at two European national energy institutes: the Energy Research Centre of the Netherlands (ECN) and the Spanish National Renewable Energy Centre (CENER). Both ECN and CENER operate pilot-scale torrefaction plants. The PATRIG plant at ECN can thermally upgrade 50–100 kg feedstock per hour and is based on a moving bed reactor which is directly heated [33,8].

CENER’s Second Generation Biofuels Centre in Aoiz houses a torrefaction reactor, which can produce some 500 kg of torrefied biomass per hour. It is based on a rotary-drum design which is indirectly heated using a thermal fluid [9]. Pelletisation takes place within the same facilities.

2.2. Feedstock for ECN

Two abundant types of Finnish feedstock were selected for torrefaction at ECN:

- whole-tree (predominantly pine) wood chips from forest-thinning operations
- logging residues (branches and needles) crushed and sieved to a particle size of 8–32 mm.

These were produced and dried at the Kokemäki heating station in Western Finland and shipped to The Netherlands. Based on preliminary thermogravimetric analysis of Finnish feedstock and single-pellet press trials which indicated ease of pelletisation, three different torrefaction temperatures were chosen.

2.3. CPM pelletisation

After torrefaction at ECN, pelletisation was done at the laboratory of CPM Europe BV in Amsterdam. Torrefied materials were first reduced in size using a hammer mill whose power consumption ranged from 10 to 15 kW h t^{-1}. Pelletisation was done using a semi-industrial ring-dye pellet press, model CPM 2016-2, with nominal motor load of 75 kW with a 6 mm ring dye. Electric power consumption during pelletising was 70–80 kW h t^{-1} with whole-tree wood chips and approximately 90 kW h t^{-1} using logging residues. The total amount of pellets produced at CPM was roughly 1500 kg.

2.4. CENER pellets

The torrefied pellets produced at CENER were made from local beech stem wood under the supervision of the authors during a research visit to Navarre in October 2011. The torrefaction temperature and other process parameters were chosen by CENER personnel based on their experience with the intent of demonstrating torrefaction and the pellet production process forming part of a research visit in the EU BIOCLUS Project.

Table 1 summarises the pellet samples used in this study including reactor technology, torrefaction temperature, residence time and approximate mass yield.

The torrefied pellets were shipped to Finland from The Netherlands and Spain in late 2011. In addition to torrefied pellets, a sample of conventional wood pellets was also characterised along with samples.

The measurements described here were carried out at the laboratories of the Technical Research Centre of Finland (VTT). Determination of gross calorific values and ultimate and proximate

Table 1
Description of pellet samples used in this study. Symbols used refer to (a) Produced by Vapo Oy, contains typically less than 1% starch as binder, (b) approximately 3% wheat flour, (c) temperature range 270–273 °C.

Sample number	Sample name	Torrefaction temperature (°C)	Mass yield (%)	Feedstock material	Technology
1	Wood pellet[a]	Untreated	–	Sawdust & cutter shavings (*Pinus sylvestris*)	Conventional pellet production
2	Pine 235	235	91	Whole-tree pine chips (*Pinus sylvestris*)	Moving-bed reactor, direct heating. Residence time 30–45 min. (ECN)
3	Pine 245	245	81		
4	Pine 255	255	77		
5	Lres 240	240	91	Logging residue chips	
6	Lres 250	250	83	Logging residue chips with binder[b]	
7	Beech 270	270[c]	76	Beech stem wood chips (*Fagus sylvatica*)	Rotary-drum rector, indirect heating. Residence time 40–45 min. (CENER)

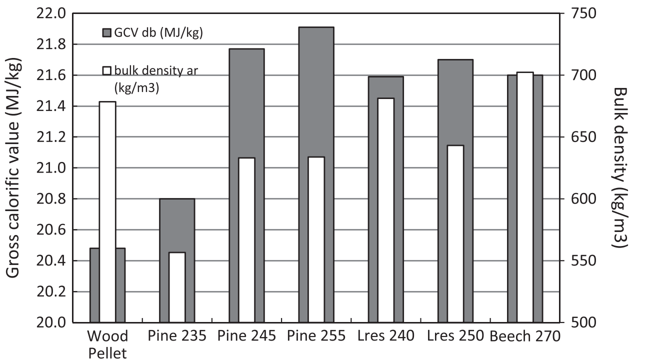

Fig. 1. Measured gross calorific value (left axis) and bulk density (right axis) of the seven pellet samples. Both measurements were carried out according to standard methods (EN14918, EN 15103).

analysis of samples took place at VTT in Espoo. Other measurements on pellets were done at VTT laboratories in Jyväskylä during spring 2012. Equilibrium moisture content determination of loose beech feedstock was done in the Department of Chemistry at the University of Jyväskylä.

2.5. Calorific value, bulk density and energy density

Gross calorific value measurements of samples (see Fig. 1) were carried out at constant volume and at a reference temperature of 25 °C using a bomb-type calorimeter according to standard procedure (EN 14918). In measuring gross calorific value using this method, the gaseous H_2O formed from combustion products is condensed to a liquid. In practice, however, fuels are combusted at constant pressure and condensation of H_2O is not assumed; it exits the power plant along with combustion gases. The so-called net calorific value takes this into account.

Eq. (1) gives the net calorific value as a function of moisture content M in addition to the content of hydrogen $w(H)_d$, oxygen $w(O)_d$ and nitrogen $w(N)_d$ in the dry fuel.

$$q_{p,net,m} = \{q_{V,gr,d} - 212.2 \times w(H)_d - 0.8 \times [w(O)_d + w(N)_d]\} \times (1 - 0.01M) - 24.43M \quad (1)$$

The coefficients in Eq. (1) stem from the conversion of caloric value at constant volume to constant pressure conditions and from the enthalpy of vapourisation for water at 25 °C. For derivation of the equation the reader is directed to annex C of the European standard for determination of calorific value (EN 14918). This value is often called *as received* value because moisture content is easily measured on-site when fuel is received at power plants. Consequently this value determines the price of the fuel.

$$\sigma = \rho \cdot q \cdot c_E \quad (2)$$

The bulk density of the pellet samples was measured using standard methods (see Fig. 1). with a five-litre cylindrical container (EN 15103). The energy density (Eq. (2)) represents how much energy is contained within a cubic metre of space (GJ m^{-3}) and has practical use in determining storage volumes and transport expenses based on fuel needs. Calculated σ values only have meaning when ρ and q correspond to the same level of moisture in the fuel. For example, if q is the net calorific value at a moisture content M then ρ must also be of same moisture content. The bulk density at different moisture contents can be calculated by assuming that moisture does not affect the volume of fuel, using the definition of moisture content on wet basis:

$$m_M = m_d\left(\frac{M_w}{100 - M_w}\right) \quad (3)$$

2.6. Determination of equilibrium moisture content

The static conditions necessary for determining EMC of pellets were provided through use of a custom-built condensing dryer used as a climatic testing chamber (Fig. 2). The device allows measurement and regulation of temperature, humidity and air flow at atmospheric pressure. The conditions chosen for the EMC measurement were a temperature of 22 °C and RH of 85%. The uncertainty in humidity regulation is estimated at ±2%. Moisture content is reported on a wet basis and determination was carried out according to the existing standard for solid biofuels (EN 14774). Prior to measurements, samples were kept in the laboratory for several weeks where ambient temperature is maintained

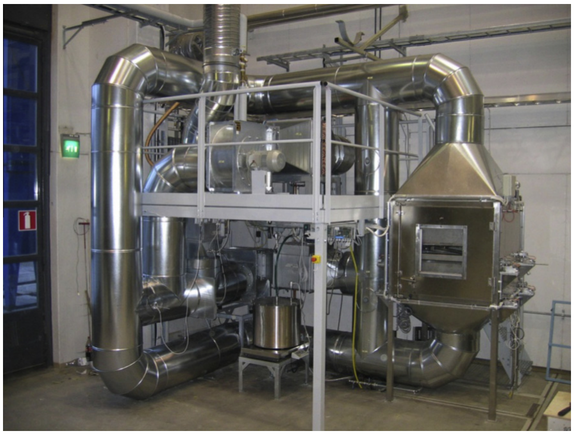

Fig. 2. The condensing dryer at VTT used as a climatic testing chamber for the determination of equilibrium moisture content of pellet samples at 22 °C and 85% RH. The sample chamber with observation window is the cubical compartment located on the right-hand side of the photograph.

at 20 °C with approximate relative humidity of 50%. Herein the term *as received* refers to samples kept under these conditions. In what follows, the methodology of the EMC measurement is described.

The climatic chamber was turned on and allowed to stabilise at test conditions. A sample of each bio-coal pellet type (exceeding 300 g) was placed in an open tray made of aluminium foil. The initial moisture content of each sample was then measured. The trays containing the samples were placed in the chamber. At regular intervals the trays were removed from the chamber and their mass was measured using an electronic laboratory balance. The order in which each tray was weighed was the same for all subsequent measurements. The weighing of all the trays took place within a few minutes time during which the climatic chamber was closed and maintained at test conditions. The measurements continued until the mass of the all the samples remained constant – this occurred within an approximate twenty-four-hour period. The moisture content of Sample 1 was determined separately from that of other samples and used two batches of samples whose average moisture content appears in the data. The initial moisture content of the samples was also measured at the start of the test for EMC determination.

The EMC as a function of relative humidity was measured for both untreated and torrefied beech wood – the same material used in producing Sample 7. Untreated and torrefied beech wood chips obtained from CENER during production of torrefied pellets, were milled using a Retsch SM100 cutting mill with a 1 mm bottom sieve which according to the manufacturer results in 75–80% of the milled material having a particle size less than 0.5 mm. It was observed however that the milled torrefied beech produced a greater amount of dust and otherwise appeared finer than the untreated beech despite the use of the same mill and sieve. Untreated and torrefied beech sample mass used to determine EMC were in the range of 180–280 and 240–310 mg (±5 mg) respectively.

Conditions of constant relative humidity were realised by using super-saturated solutions of various salts (Table 2) in sealed half-litre plastic containers along with untreated and torrefied samples. Each of the samples (prepared in triplicate) was kept in an open plastic 15 mL sample container (with lid stored beneath) whose mass was recorded beforehand. Samples were weighed every other day until mass appeared constant (within 0.5%). For most of the samples this occurred after about eight days but measurements continued for 19 days. The lid of each sample container was put in place immediately upon removal from the constant RH conditions in order to minimise absorption or drying due to ambient atmosphere while weighing.

Calculation of RH was done using polynomial equations of the form

$$RH = \sum_{i=0}^{3} A_i T^i \tag{4}$$

which were derived by Greenspan from a compilation of fitted data [34]. Salt types, polynomial coefficients, valid temperature range and calculated RH at 22 °C are presented in Table 2. The EMC was determined at five different relative humidity values ranging between 11 and 94% RH. The average value of EMC from three samples was calculated at each of the five RH conditions. EMC was also determined at lower temperature using refrigeration and the same setup.

2.7. Pellet mechanical durability and hardness test

Durability was measured according to the existing standard for fuel pellets (EN 15210). The durability value describes the mass proportion of the sample which remains intact after removal of fine broken pieces (fines which pass through a 3.15 mm sieve).

Pellet hardness was determined using an *Amandus Kahl* hardness tester. The test was repeated ten times for each sample type (i.e. ten pellets of each sample) and the average value with standard deviation is reported. Being a static force measurement, the results are given in kilogram equivalency. The tester uses a series of springs to measure force. The calibration of these springs was not verified for the obtained results.

Mechanical durability and hardness tests were carried out on both the samples as received and those maintained at 22 °C and 85% RH (Section 2.6). Durability and hardness tests were also attempted on the samples after rainfall simulation (Section 2.8).

2.8. Rainfall simulation and water immersion test

Pellet samples were exposed to simulated rainfall and as described: A 1 kg sample of pellets was placed on a 450 mm diameter Retsch 3.15 mm sieve. The amount was sufficient to cover the bottom of the sieve with one layer of pellets. The sieve was placed over a container. Simulated rainfall was realised through use of a spray bottle fitted with a nozzle having many orifices. In total, 400 g of water was sprayed over each sample during a one-hour period. Runoff water drained through the sieve and was collected in the container beneath. The mass of water not absorbed by the pellets could then be determined. The total amount of water corresponds to rainfall of 2.5 mm per hour – a level of rainfall intensity which occurs in Finland statistically once every decade. This level of rain was predefined beforehand by a method of trial and error.

Pellets were also subjected to a water immersion test. A 500 g sample of each pellet type was placed in a filtration bag which was then submersed for 15 min in a five-litre container of water. By weighing the quantity of water after the immersion period, the amount of water absorbed by the pellet sample could be known. The immersion time was predefined by a method of trial and error.

3. Results

A summary of measured and calculated values is presented in Table 4. The net calorific values were calculated using Eq. (1) both as dry and at the EMC found in Section 2.6. The measured values of elemental composition from Table 3 were used in the equation. Using Eqs. (2) and (3) the energy density of pellet samples was calculated on a dry basis and at EMC. The EMC values for the samples were assumed to be the same as the last measured data points in

Table 2
Salts used in determination of equilibrium moisture content. Relative humidity at 22 °C as calculated using Eq. (4), coefficients A_i within valid temperature range [34].

Salt type	A_0	A_1	A_2	A_3	$T_{\min}$ (°C)	$T_{\max}$ (°C)	RH (%)
Lithium chloride (LiCl)	11.2323	−0.0082425	−2.15E−04	0	0.0	100.3	10.95
Magnesium chloride ($MgCl_2$)	33.6686	−0.007974	−1.09E−03	0	0.0	99.4	32.97
Sodium bromide (NaBr)	64.719	−0.22199	−4.02E−03	5.90E−06	5.0	80.0	57.95
Sodium chloride (NaCl)	75.5164	0.0398321	−2.65E−03	2.85E−05	0.0	80.0	75.41
Potassium nitrate (KNO_3)	96.3361	0.0112371	−4.85E−03	0	0.6	48.1	94.24

Table 3
Proximate and ultimate analysis of feedstock and torrefied samples as dry ash-free basis.

Sample	Ash (%)	Volatiles (%)	Fixed carbon (%)	C (%)	H (%)	N (%)	O (%)[*]	S (%)
Whole-tree pine chips	0.5	83.2	15.8	49.7	6.2	0.17	43.6	–
Forest residues	1.3	80.5	17.9	49.8	6.2	0.30	42.9	–
Beech stem wood	–	–	–	49.6	5.9	0.01	44.4	–
1	0.3	83.4	16.3	50.9	6.0	0.04	42.8	0.01
2	0.4	81.0	18.6	52.1	5.9	0.1	41.9	0.01
3	0.4	77.8	21.8	54.7	5.8	0.1	39.4	0.01
4	0.3	76.7	23.0	54.9	5.8	0.1	39.2	0.01
5	0.6	77.6	21.8	54.3	5.9	0.1	39.7	0.01
6	0.6	77.7	21.7	54.4	5.8	0.1	39.7	0.01
7	1.8	73.4	24.8	54.2	5.6	0.1	40.1	0.02

[*] The oxygen content (O) calculated by difference from 100%.

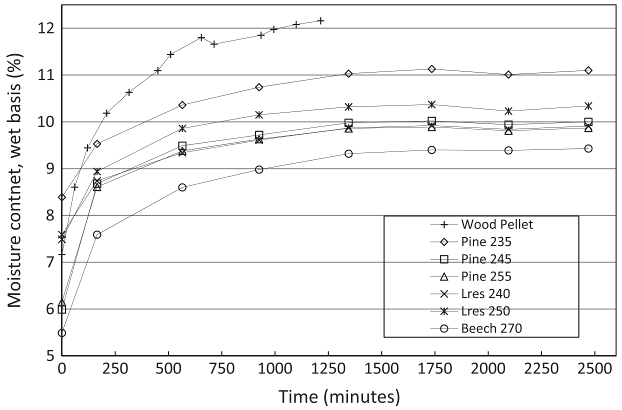

Fig. 3. Measured moisture content (data points) of seven pellet samples over time after placement in the climatic chamber. Conditions inside the chamber were held at 22 °C and RH of 85 ± 2%. Note that measurement of Sample 1 was carried out separately. Moisture content was calculated on wet basis and determination was carried out according to standard methods (EN 14774).

Fig. 3. The increase in calorific value Δq has been calculated using gross calorific values as defined in [12].

4. Discussion

The following discussion refers to the results presented in Table 4.

The measured values of $q_{V,gr,d}$ found for pellets herein range from 20.80 to 21.91 MJ kg^{-1}. The general trend in the properties of the samples is that a higher torrefaction temperature corresponds to a higher calorific value, higher energy density, a drier pellet and greater value of Δq. This is most clearly seen in those samples produced from identical feedstock (Samples 2–4 and 5–6). The highest overall gross calorific value was measured for Sample 4 whose torrefaction temperature was 255 °C. The calculated net calorific value for this sample was also the highest. As the residence time of Sample 2 through 6 is similar this agrees with recent findings which have shown that temperature is the most significant factor for torrefaction when aiming to maximise mass loss from the feedstock and increasing calorific value [16].

Pellet Samples 2–4 were produced from the same feedstock with torrefaction temperature being the only different parameter. Their measured properties show a gradation to that of an improved fuel according to torrefaction temperature. With the exception of M_{ar}, d and h_{ar} all other properties increase with temperature. Likewise, all calculated values increase with temperature. Durability is maximum for Sample 3 – the greatest value of all the softwood samples. Of the pine pellets the greatest hardness was measured for Sample 3 (see Fig. 4).

The two samples produced from logging residues can also be compared to see how temperature and the addition of a binding agent affect their properties. The hardness of Sample 6 is roughly half that of all other pellets for both as received and EMC conditions. It seems likely this stems from the binder but may also indicate given the feedstock a torrefaction temperature higher than optimal for pellet strength – for example, poor cohesion due to excess degradation of low-weight lignin polymers. Comparing properties of Sample 5 and 6 from Table 4 the general conclusion is that addition of the binder results in an inferior pellet (reduced density, durability, hardness and energy density with increase in water uptake).

At 22 °C and 85% RH the energy density of the fuels are noticeable less than on a dry basis. According to the calculated results Sample 7 was found to have the greatest energy density both on a dry basis and at its EMC. This is mostly a result of it having the highest measured bulk density (702 kg m^{-3}, $M_{ar} = 5\%$) but also likely to stem from the finding that hardwood undergoes a greater increase in calorific value during torrefaction than softwood owing to the differences in their hemicellulose composition [10,11]. The high energy density of Sample 7 compared to other samples may be a combination of this effect along with a higher torrefaction temperature and bulk density.

Table 4
Summary of measured and calculated properties of the seven pellet samples used in this study. Symbols used refer to (a) 22 °C and RH 85% (b) average of reported values [3], (c) Δq as defined in [12] and based on untreated GCV (MJ kg^{-1}) values: whole-tree pine (19.967), logging residues (20.206) and beech (19.674).

Sample	Measured Values										Calculated Values							
	$q_{V,gr,d}$ (MJ kg^{-1})	ρ_{ar} (kg m^{-3})	M_{ar} (%)	M_{emc} (%)	d_{ar} (%)	d^{a} (%)	h_{ar} (kg)	h^{a} (kg)	$M_{2.5}$ (%)	M_{15} (%)	$q_{V,gr,ar}$ (MJ kg^{-1})	$q_{p,net,d}$ (MJ kg^{-1})	$q_{p,net,M}$ (MJ kg^{-1})	ρ_d (kg m^{-3})	ρ_M (kg m^{-3})	σ_d (GJ m^{-3})	$\sigma_M{}^{a}$ (GJ m^{-3})	Δq (%)
Wood pellet	20.48	678.5	6.67	11.66	98.0	(98.2)[b]	20.9 (0.5)	(19)[b]	31	77	17.73	19.17	16.61	633	717	12.97	11.91	0.00
Pine 235	20.80	556.6	7.89	10.60	80.0	69.2	15.1 (4.7)	18.3 (3.1)	33	66	17.78	19.51	17.13	513	573	10.66	9.82	4.17
Pine 245	21.77	633.1	5.49	9.50	92.0	86.6	20.7 (0.6)	19.4 (3.1)	32	53	19.25	20.51	18.28	598	661	13.03	12.09	9.03
Pine 255	21.91	633.8	5.65	9.37	88.2	81.6	18.8 (3.6)	20.3 (1.8)	32	51	19.34	20.65	18.43	598	660	13.10	12.16	9.73
Lres 240	21.59	681.3	7.09	9.41	89.1	84.3	17.8 (2.9)	18.6 (3.1)	32	46	18.69	20.31	18.12	633	699	13.67	12.66	6.85
Lres 250	21.70	643.2	6.99	9.84	86.8	79.1	9.8 (1.7)	10.6 (3.5)	33	50	18.84	20.44	18.12	598	664	12.98	12.02	7.39
Beech 270	21.60	702.3	4.99	8.93	97.1	95.5	19.7 (2.4)	20.4 (1.6)	32	39	19.24	20.38	18.28	667	733	14.41	13.39	9.79

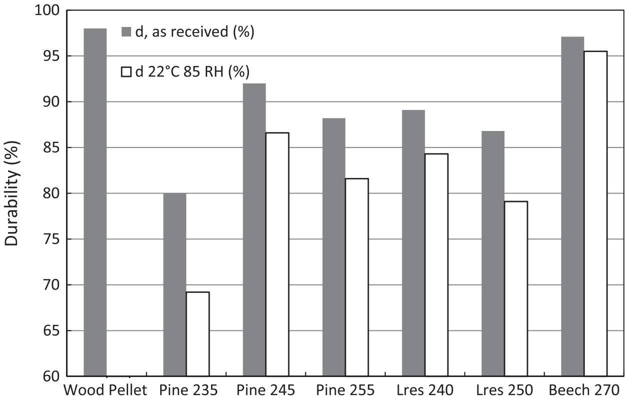

Fig. 4. Durability of pellets, measured according to standard methods (EN 15210), at laboratory conditions and at EMC conditions of 22 °C and RH 85%. The values are average values from two measurements from each sample batch. Note that there is no data for Sample 1 at 22 °C RH 85%.

The range of bulk density values (556–702 kg m^{-3}) had a lower range than those reported by Larsson et al. but this may be due to lower torrefaction temperature and differing wood type. They report a range of 630–710 kg m^{-3} for torrefied spruce pellets with moisture content between 1% and 5% [4]. However, they do not report RH nor ambient temperature conditions corresponding to this moisture content.

It is noted that the energy density of the conventional wood pellets in this study was found to be relatively high. The energy density of Sample 1 appears at the top end of the Finnish range (12 GJ m^{-3}). This should be considered when evaluating the benefits of torrefied pellets overs conventionally produced ones.

The measured EMC for the torrefied samples ranged from 8.9% to 10.6% at 22 °C and 85% RH. All samples were found to have a lower EMC than conventional wood pellets whose value was found to be 11.7%. The EMC of Sample 7 (8.9%) was the lowest of all torrefied pellet samples – a difference of 2.7% on a wet basis.

The EMC of Sample 7 is plotted along with EMC isotherms for milled beech in Fig. 5. At 85% RH it agrees within experimental uncertainties with straight lines connecting data points. It can be seen that the absolute difference in EMC between untreated and torrefied beech is greatest at high RH. Isotherms show that EMC depends strongly on relative humidity and inversely on temperature.

The durability (as received) of the samples 2–6 ranged from 80% to 92%. The only sample of torrefied pellets to meet the minimum normative durability classification was found to be Sample 7 whose durability was 95.5% (see Fig. 4). The lowest durability (69%) was measured for pellets made from whole-tree pine feedstock at 22 °C and 85% RH. The durability of all measured samples was found to decrease at 22 °C and 85% RH compared to those as received. The size distribution of fine particles was not measured in this study but the amount of fine material found in accessing durability is significantly greater than the nominal level for conventional wood pellets. Excluding Sample 7, the mass proportion of fines ranged from 13.4 to 30.8% a range similar to that found by Larsson et al. [4] for torrefied spruce pellets.

The hardness of all torrefied pellets was found to be less than conventional wood pellets (Fig. 6). Hardness of torrefied pellets was observed to increase slightly at 22 °C and 85% RH compared to that as received. The only exception to this trend was Sample 3 whose hardness decreased. The reason for this exception is not known but may not be of significance considering sample size and uncertainties. The lowest hardness value (9.8 kg) was found for pellets made from logging residues.

The moisture content of all seven samples was similar falling between 31% and 33% after rainfall simulation. This indicates that relatively heavy rainfall results in short-duration wetting to the same extent regardless of torrefaction conditions. Immediately following the simulation, durability and hardness tests were again attempted on torrefied samples. With the exception of Sample 7 this was not possible because all samples disintegrated due to moisture. These results have not been presented.

The moisture content of pellet samples after 15-min immersion in water indicates that higher torrefaction temperature results in a more water-resistant pellet. Conventional wood pellets (Sample 1) were found to have the highest moisture content (77%) and Sample 7 the lowest (39%). Between these extremes samples produced from the same feedstock (Samples 2–4) showed a decrease in M_{15} as torrefaction temperature increased. Torrefied logging residue pellets containing binder (Sample 6) showed 4% higher moisture content. In this case, the reason for higher retained moisture may be the presence of the binder (3% wheat flour) whose absorption capacity is expected to be the same as other untreated biomass. Based on the 15-min immersion test results, outdoor heap storage of torrefied pellets characterised here would not appear to be sensible given the energy and care put into their production. Therefore it is expected that torrefied pellets of the types studied herein would require similar storage methods as conventional wood pellets.

The relative calorific value increase (Δq) through torrefaction is seen to range from 4.1% to 9.8% for torrefied pellets. It is noted that this range is less than that achieved in laboratory-scale studies on

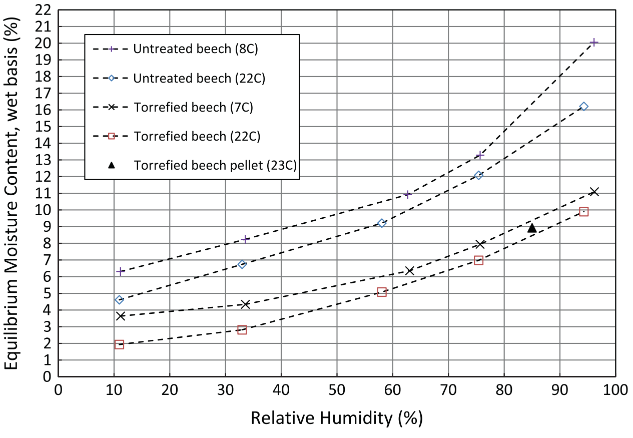

Fig. 5. Measured isothermal curves for equilibrium moisture content (wet basis) of untreated (at 8 and 22 °C) and torrefied beech stem wood (at 7 and 22 °C). The EMC of pellet Sample 7 at 22 °C and 85% RH is also shown.

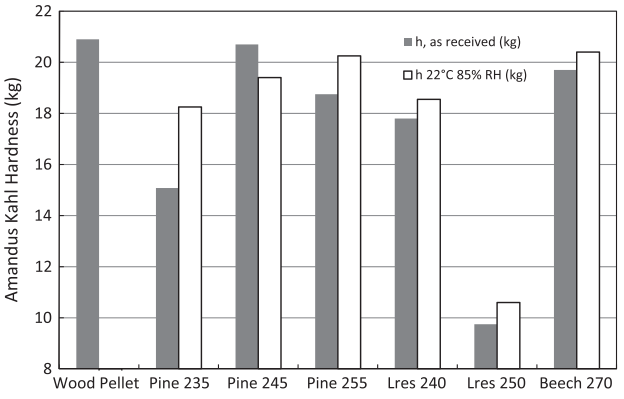

Fig. 6. Hardness measurement results of pellet samples as received and at EMC conditions of 22 °C and RH 85%. Presented values are averages of ten measurements. Note that there is no data for Sample 1 at 22 °C RH 85%.

Table 5
Comparison of pellet properties: conventional wood pellets and torrefied pellets as reported by Larsson [4] and Bergman [26]. Symbols refer to (a) from [3] (b) Dry ash-free (c) Lower heating value (LHV) reported (d) calculated using LHV (e) After 15-h water immersion (f) Based on improvement values reported as decimal fractions (na) not available.

Property	Wood pellets[a]	Larsson et al. [4]	Bergman [26]	Herein
$q_{V,gr,d}$	18.8–19.0	22.5[b]	20.4–22.7[c]	20.5–21.9
$q_{p,net,m}$	16.7–17.9	21.0[d]	19.9–21.6	17.8–19.3
Δq	0.0	10.8	15–28[d]	4.2–9.8
M_{ar}	7–12	1–5	1–5	5–8
ρ_{ar}	560–690	683–713	750–850	557–702
σ_{ar}	10.5–13.1	15.4–16.0[b]	14.9–18.4	10.7–14.4
M_{15}	na	na	7–20[e]	39–66
h	17–21	na	28.5–38.0[f]	9.8–20.7
d	>97.5	82.8–90.3	>97.5	80–97

(non-densified) torrefied biomass [12]. This is not unexpected because herein extreme torrefaction conditions were avoided to ensure successful pelletisation of feedstock – a compromise necessary for producing a densified product. The greatest improvement in calorific value was seen in Sample 7.

The measured and calculated results found in this study are compared where possible to those previously reported on semi-industrially produced pellet properties and to conventional wood pellets in Table 5.

The gross calorific values of torrefied pellets found here agree with Larsson's dry ash-free value. As received moisture contents are much higher than those of other authors and as a result the net calorific values are correspondingly lower. Bergman reports only net calorific values (lower heating value) which are of similar magnitude as gross values found here. Bulk density values are in better agreement with Larsson but not with Bergman whose reported values are notably higher. Summarising the values in Table 5 the biggest differences found are in values for bulk density, received moisture content, net calorific value, energy density, M_{15} and pellet hardness.

In general, the results found here agree well with the most recent study [4] excluding EMC both of pellets and torrefied beech wood and hardness results which to the authors' knowledge have not previously been reported in peer-reviewed literature.

Durability and hardness of torrefied pellet samples were found to be problematic both in this study and by that of Larsson. If the solution to this is not found by use of higher die temperatures or other innovations, perhaps its importance for large-scale co-firing applications should be revisited. For example, the quality of conventional wood pellets is important for small-scale combustion behaviour in domestic pellet boilers but less so for industrial use where flue gases can be better regulated and cleaned [35]. If an analogous case is found for the issue of durability then as also suggested by Obernberger et al. perhaps pellet standards could be modified to allow for lower durability values for industrial use of torrefied pellets if greater fines content is not problematic.

In terms of fuel properties, Sample 7 showed the most beneficial results: lowest equilibrium moisture content (8.9%), the highest energy density (14.4 GJ m^{-3}), best durability (95.5%) and the greatest Kahl hardness (20.4 kg). At a temperature of 22 °C and 85% RH, the net energy density of these pellets was calculated to be 13.4 GJ m^{-3}; 12.6% greater than the energy density of wood pellets (Sample 1) and 13.6% greater than the typical mid-range value of Finnish wood pellets (Table 5).

5. Conclusions

From the results of this study the following can be stated with regard to the produced pellet samples:

- Feedstock choice has a strongly influence on properties of torrefied pellets.
- Durability of torrefied pellets is problematic compared to wood pellets.
- Outdoor heap storage of torrefied pellets is not recommended.
- Logging residues do not seem to be an optimal feedstock choice for torrefied pellets.
- Wheat flour does not appear suitable as binder for torrefied pellets production due to water absorption.
- Pelletising using high die temperature (above 170 °C) should be investigated.

The rationale behind torrefied pellet production is to achieve a product that is superior to conventional wood pellets. The results herein indicate that superior properties (dry basis) include higher calorific value (4–10%), greater energy density (max. 11%), lower EMC, and resistance to moisture. Mechanical durability of torrefied pellets with one exception (Sample 7) was found to be inferior ranging from 80% to 92%. The hardness of all torrefied pellets was less than conventional pellets. Additionally, EMC isotherms for torrefied beech wood have been presented.

Further research on the properties of torrefied pellets is needed. Studies should focus on the entire production chain as well as end use investigation on milling, conveying and direct co-firing properties at the power plant. This is important because torrefied pellets are meant to be a fossil coal replacement and enable greater co-firing rates.

Acknowledgements

Collaboration between authors was made possible through the BIOCLUS Project funded by the EU Seventh Framework Programme (FP7). Part of the experimental work described herein was carried out through the Finnish national BioRefine Project and partly through the European Project SECTOR (Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction). The authors would like to thank the personnel from the Biomass Energy Department of CENER for kind hospitality during their visit to Sarriguren. The Fortum Foundation is acknowledged for financial support during the writing of this manuscript.

References

[1] Kjärstad J, Johnsson F. The European power plant infrastructure – presentation of the chalmers energy infrastructure database with applications. Energy Policy 2007;35(7):3643–64.
[2] Van Loo Sjaak, Koppejan Jaap. Handbook of biomass combustion and co-firing. Enschede: Twente University Press; 2002.
[3] Alakangas E. Properties of wood fuels used in Finland – BioSouth Project, Report. PRO2/P2030/05; 2005.
[4] Larsson SH, Rudolfsson M, Nordwaeger M, Olofsson I, Samuelsson R. Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce. Appl Energy 2013;102:827–32.
[5] Basu P, Dhungana A, Rao S, Acharya B. Effect of oxygen presence in torrefier. J Energy Inst 2013;86(3):171.
[6] Wang C, Peng J, Li H, Bi XT, Legros R, Lim CJ, et al. Oxidative torrefaction of biomass residues and densification of torrefied sawdust to pellets. Bioresour Technol 2013;127:318–25.
[7] Bridgeman TG, Jones JM, Shield I, Williams PT. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel 2008;87(6):844–56.
[8] Bergman PCA, Boersma AR, Zwart RWR, Kiel JHA. Torrefaction for biomass co-firing in existing coal-fired power stations. ECN-C-05-013; 2005.
[9] Celaya J, Gil J. Evaluation of torrefaction and pelletization process to transform biomass in a biofuel suitable for cocombustion. In: Proceedings at the 16th European biomass conference & exhibition, June 2008; 2008.
[10] Prins MJ, Ptasinski KJ, Janssen FJJG. Torrefaction of wood: Part 1. Weight loss kinetics. J Anal Appl Pyrol 2006;77(1):28–34.
[11] Prins MJ, Ptasinski KJ, Janssen FJJG. Torrefaction of wood: Part 2. Analysis of products. J Anal Appl Pyrol 2006;77(1):35–40.
[12] Agar D, Wihersaari M. Bio-coal, torrefied lignocellulosic resources – key properties for its use in co-firing with fossil coal – their status. Biomass Bioenergy 2012;44:107–11.

[13] Phanphanich M, Mani S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. Bioresour Technol 2011;102(2):1246–53.

[14] Yan W, Acharjee T, Coronella C, Vásquez V. Thermal pretreatment of lignocellulosic biomass. Environ Prog Sustain Energy 2009;28(3).

[15] Arias B, Pevida C, Fermoso J, Plaza MG, Rubiera F, Pis JJ. Influence of torrefaction on the grindability and reactivity of woody biomass. Fuel Process Technol 2008;89(2):169–75.

[16] Bridgeman TG, Jones JM, Williams A, Waldron DJ. An investigation of the grindability of two torrefied energy crops. Fuel 2010;89(12):3911–8.

[17] Deng J, Wang G, Kuang J, Zhang Y, Luo Y. Pretreatment of agricultural residues for co-gasification via torrefaction. J Anal Appl Pyrol 2009;86(2):331–7.

[18] Sjöström E. Wood chemistry – fundamentals and applications. 2nd ed. London (UK): Academic Press Inc.; 1993.

[19] Khazraie Shoulaifar T, Demartini N, Ivaska A, Fardim P, Hupa M. Measuring the concentration of carboxylic acid groups in torrefied spruce wood. Bioresource Technol 2012;123(0):338–43.

[20] Acharjee TC, Coronella CJ, Vasquez VR. Effect of thermal pretreatment on equilibrium moisture content of lignocellulosic biomass. Bioresour Technol 2011;102(7):4849–54.

[21] Singh RN. Equilibrium moisture content of biomass briquettes. Biomass Bioenergy 2004;26(3):251–3.

[22] Repellin V, Govin A, Rolland M, Guyonnet R. Energy requirement for fine grinding of torrefied wood. Biomass Bioenergy 2010;34(7):923–30.

[23] Huéscar Medina C, Pzhylaktou HN, Sattar H, Andrews GE, Gibbs BM. The development of an experimental method for the determination of the minimum explosible concentration of biomass powders. Biomass Bioenergy 2013;53(0):95–104.

[24] Peng JH, Bi HT, Lim CJ, Sokhansanj S. Study on density, hardness, and moisture uptake of torrefied wood pellets. Energy Fuels 2013;27(2):967–74.

[25] Peng JH, Bi XT, Sokhansanj S, Lim CJ. Torrefaction and densification of different species of softwood residues. Fuel 2013;111:411–21.

[26] Bergman PCA. Combined torrefaction and pelletisation – the TOP process. ECN-C-05-073. Petten (NL): Energy Research Centre of the Netherlands; 2005.

[27] Li H, Liu X, Legros R, Bi XT, Jim Lim C, Sokhansanj S. Pelletization of torrefied sawdust and properties of torrefied pellets. Appl Energy 2012;93(0):680–5.

[28] Ruiz Celma A, Cuadros F, López-Rodríguez F. Characterization of pellets from industrial tomato residues. Food Bioprod Process 2012;90(4):700–6.

[29] Kaliyan N, Vance Morey R. Factors affecting strength and durability of densified biomass products. Biomass and Bioenergy 2009;33(3):337–59.

[30] Stelte W, Clemons C, Holm JK, Sanadi AR, Ahrenfeldt J, Shang L, et al. Pelletizing properties of torrefied spruce. Biomass Bioenergy 2011;35(11):4690–8.

[31] Stelte W, Nielsen NPK, Hansen HO, Dahl J, Shang L, Sanadi AR. Pelletizing properties of torrefied wheat straw. Biomass Bioenergy 2013;49:214–21.

[32] Kaliyan N, Morey RV. Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. Bioresour Technol 2010;101(3):1082–90.

[33] Kiel JHA, Verhoeff F, Gerhauser H, Meuleman B. BO2-technology for biomass upgrading into solid fuel – pilot-scale testing and market implementation. ECNM-08-036. Petten (NL): Energy Research Centre of the Netherlands; 2008.

[34] Greenspan L. Humidity fixed points of binary saturated aqueous solutions. J Res – Natl Bureau Stand 1977;81A:89–96.

[35] Obernberger I, Thek G. Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Biomass Bioenergy 2004;27(6):653–69.